Atomic and Molecular Physics Program

Date: 5 March 2013

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Program Officer
AFOSR/RTB
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

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NAME: Tatjana Curcic

BRIEF DESCRIPTION OF PORTFOLIO:
Understanding interactions between atoms, molecules, ions, and radiation.

SUB-AREAS IN PORTFOLIO:

- **Cold Quantum Gases**
  - Strongly-interacting quantum gases
  - Ultracold molecules
  - New phases of matter
  - Non-equilibrium quantum dynamics
- **Quantum Information Science (QIS)**
  - Quantum simulation
  - Quantum communication
  - Quantum metrology, sensing, and imaging
  - Cavity optomechanics

Outline

- **Quantum Communication: Quantum Memories and Light-Matter Interfaces (FY11 MURI)**
  - **Strongly Interacting Photons: Vladan Vuletic (MIT)**
    - Cavity-based single-photon transistor where one photon can switch 1000 photons: Wenlan Chen, *et al, preprint*
  - **Atomic Quantum Memories in Nano-Scale Optical Circuits: Jeff Kimble, Oskar Painter (CalTech)**
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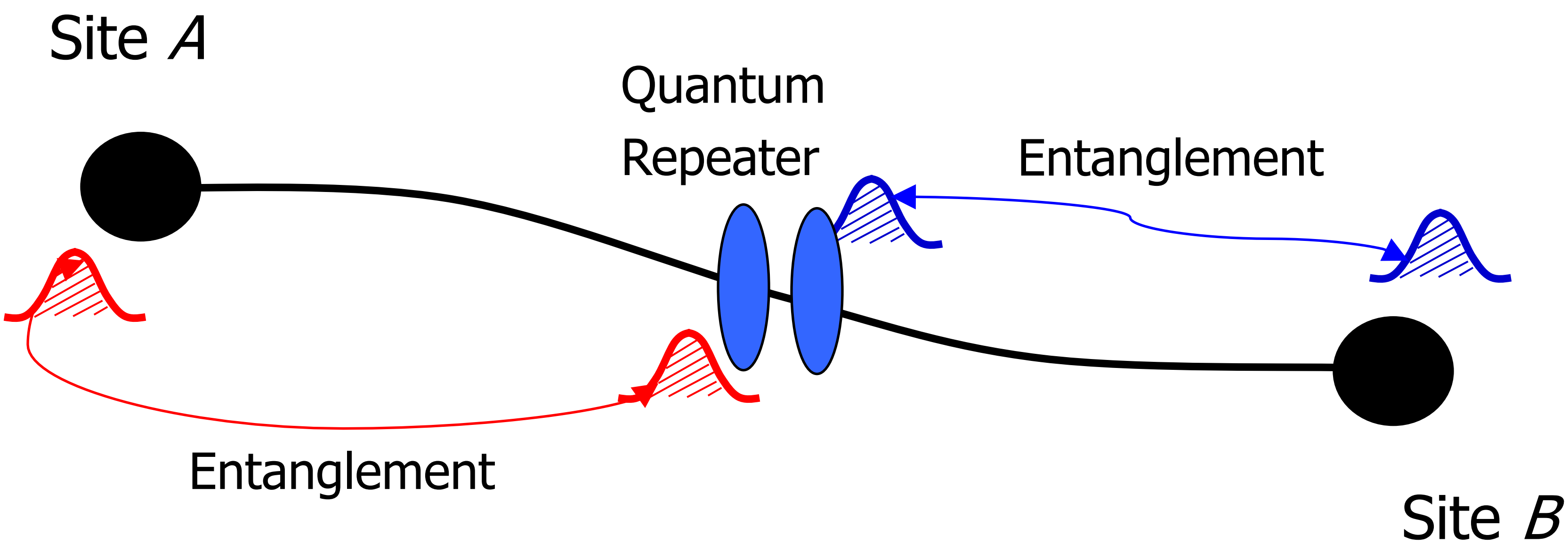
Quantum Networks

Enable ultra-secure communication over fiber network or free space

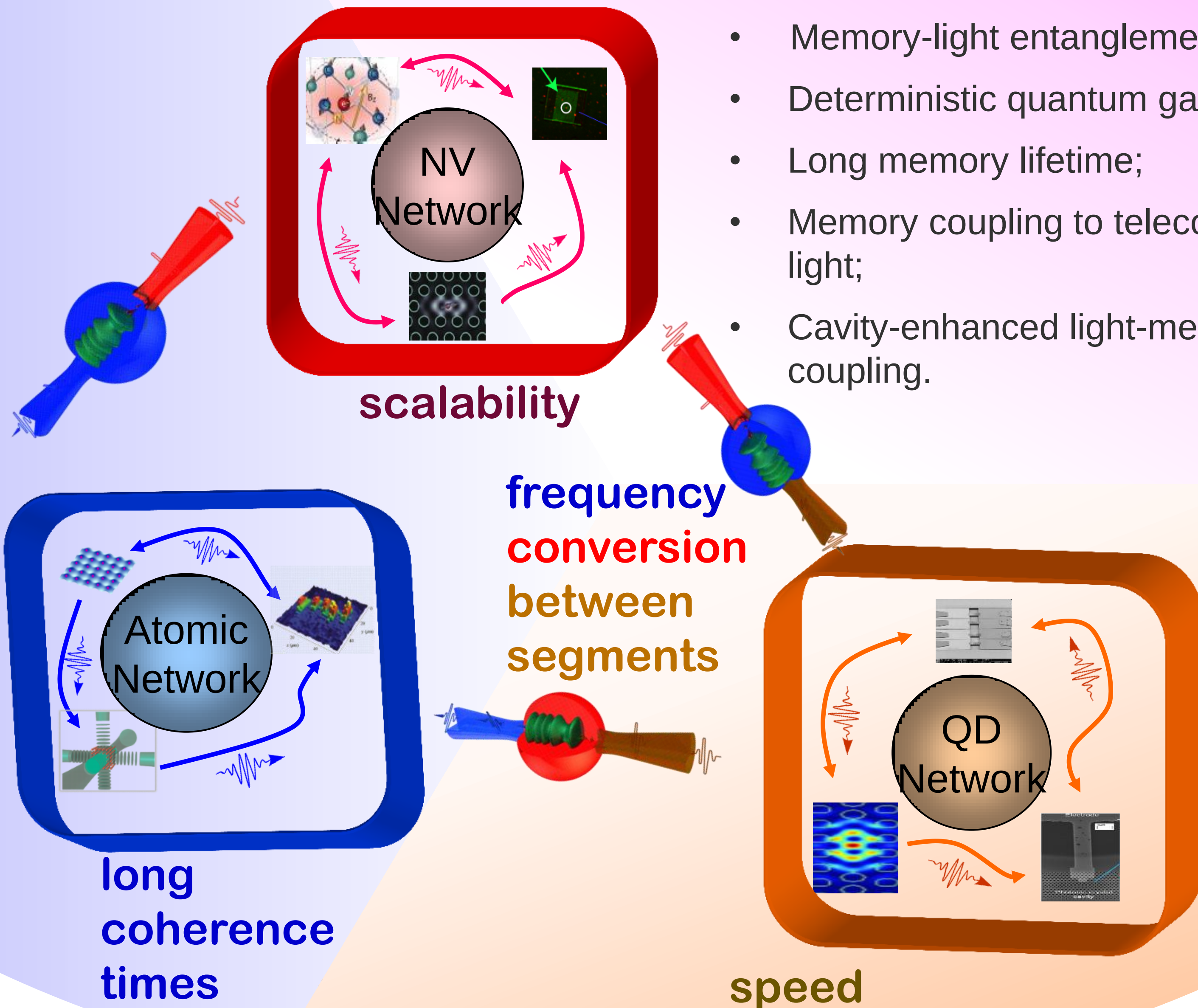


<u>Requirements</u>
- **Light-matter interface**
- **Quantum memory**
- **Elementary quantum gates**

“The quantum internet”, H. J. Kimble, *Nature* **453**, 1023 (2008)

Quantum Memories and Light-Matter Interfaces (FY11 MURI)

- Memory-light entanglement;
- Deterministic quantum gates;
- Long memory lifetime;
- Memory coupling to telecom light;
- Cavity-enhanced light-memory coupling.



Quantum Memories and Light-Matter Interfaces (FY11 MURI)

- **Two teams:**
  - **GaTech** (PI: A. Kuzmich): U. Michigan, Columbia, Harvard, U. Wisconsin, Stanford, MIT
  - **UCSB** (PI: D. Awschalom): Iowa State U., U. Iowa, Harvard, CalTech
- **Accomplishments in 1st year:**

Atoms:

- **16s atomic memory (GaTech)**
- **Rydberg single-photon source (GaTech)**
- **Nonlinearity at the single-photon level (MIT/Harvard)**
- **Single-photon transistor (MIT)**
- **Coupling atoms with nanofiber cavities (CalTech)**
- **Atomic mirrors, integration with nanophotonics (CalTech)**

NV-diamond:

- **Spin-photon interface: quantum interference demonstrated (Harvard)**
- **NV qubit coherence lifetime > 1s (Harvard)**
- **All-optical control of of NV spins (UCSB)**
- **Stable NV centers in bulk and nanobeams**
- **Integrated diamond networks for nanophotonics (Harvard)**
- **Engineering shallow spins with N delta-doping (UCSB)**
- **SiC and other color centers (UCSB, U. Iowa)**

Quantum dots:

- **New scheme to efficiently couple a single QD electron spin to an optical nanocavity (Stanford)**

- **More than 40 papers, including 6 Nature/Science and 10 PRLs.**

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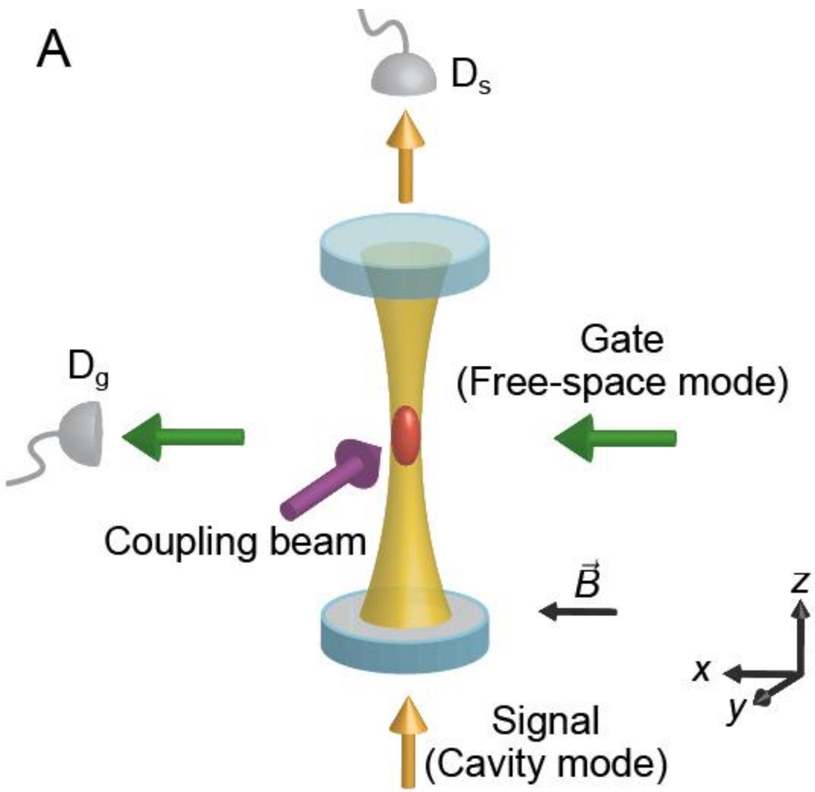
Photon-photon switch and transistor

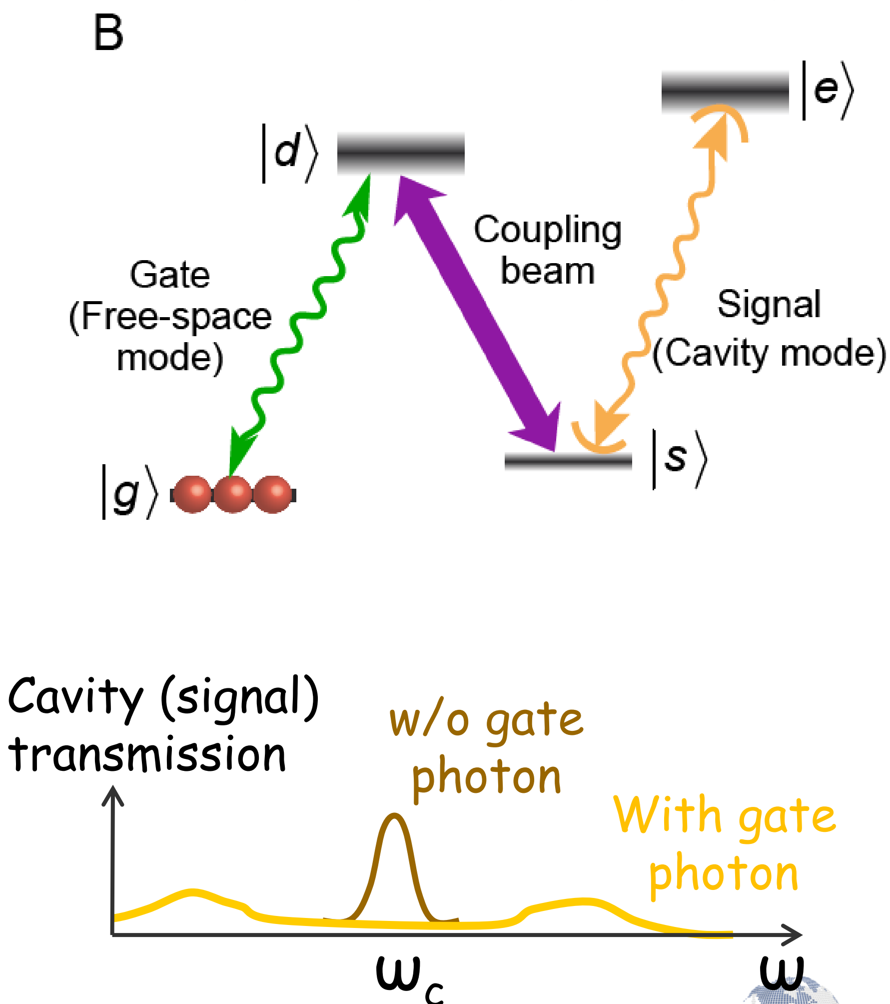
Vladan Vuletic, MIT

Wenlan Chen, *et al, preprint*

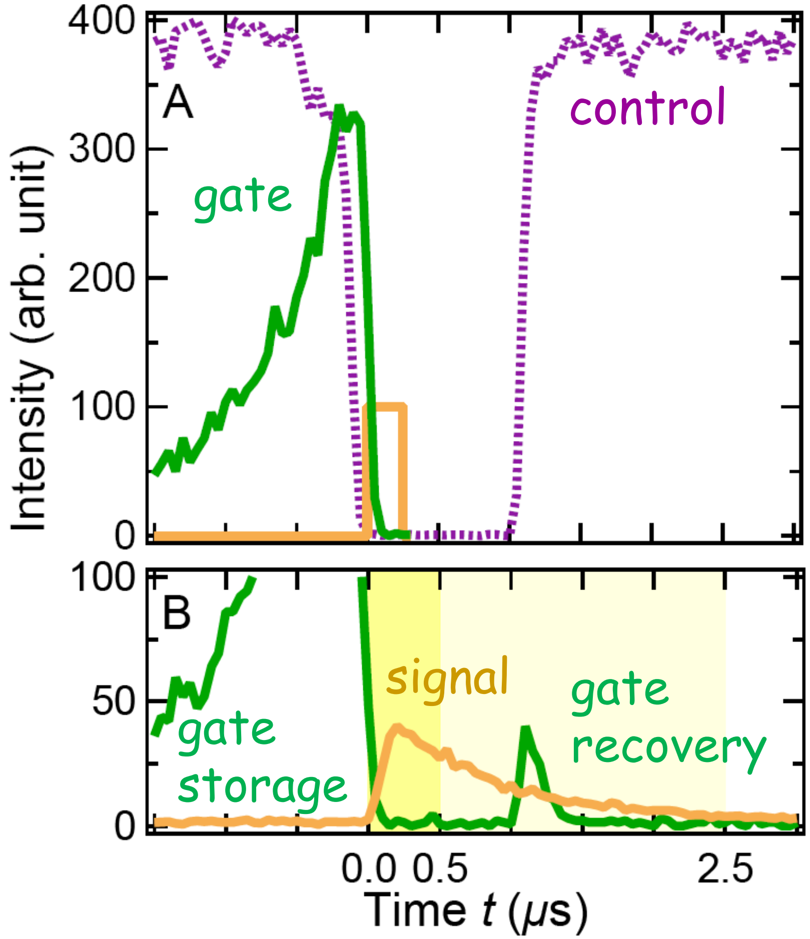
Experimental setup

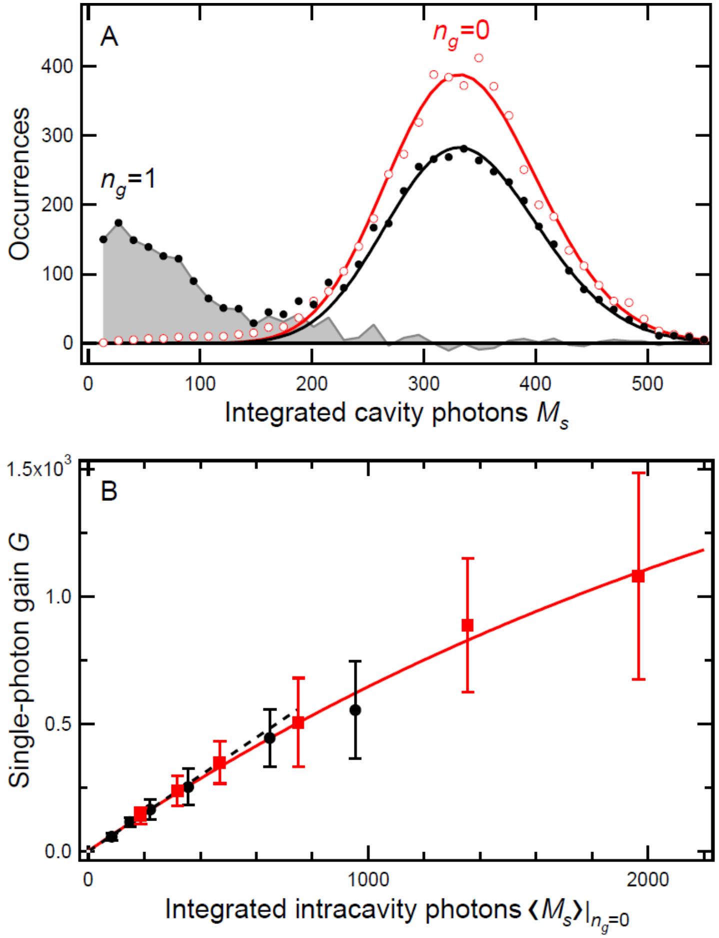


Atomic level scheme



Single-photon transistor with gain: switching 1000 photons with one



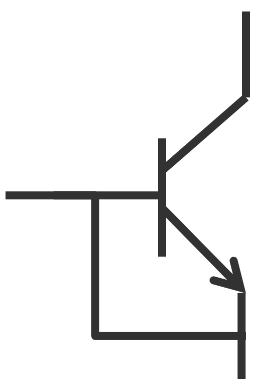


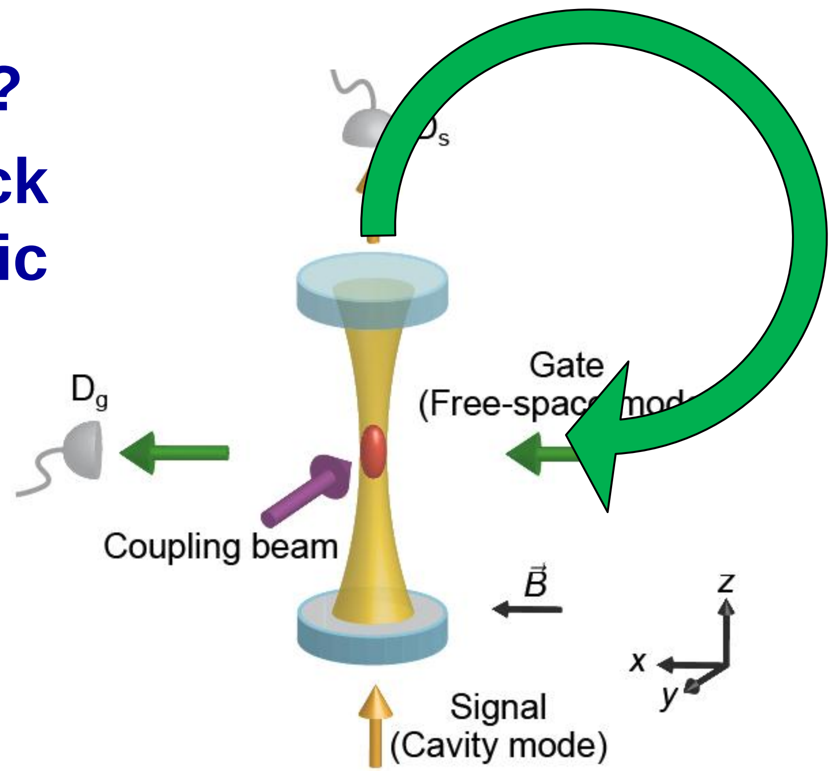
Single gate photon suppresses signal transmission by factor of 6.

More than 1000 signal photons can be blocked by a single photon!

Future Possibilities

- **Quantum non-demolition detector for traveling optical photons**
- **Deterministic photon-photon phase shift**
- **Photon-photon quantum gates?**
- **All-optical circuits with feedback and gain in analogy to electronic circuits**





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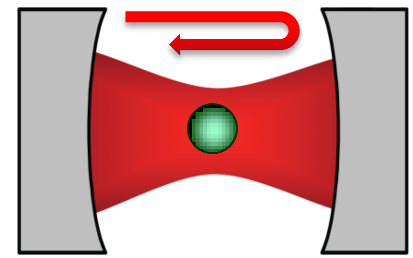
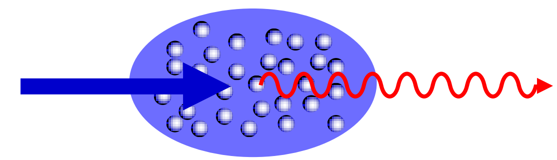
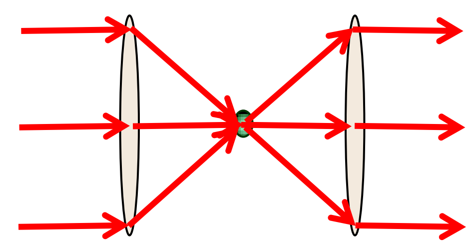
Nanofiber Optical Trap for Cold Atoms

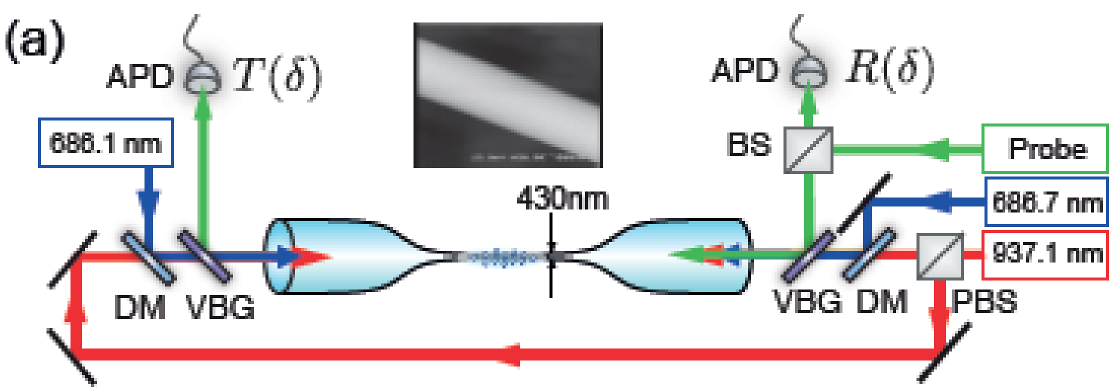
Jeff Kimble, CalTech

- **Strong interactions of single photons and atoms**
  - ➢ **Multi-pass interactions and small mode volume in an optical cavity (cQED)**
  - ➢ **Large optical depth (e.g., atomic ensembles)**
  - ➢ **Strong focusing of light**
- **A new frontier to achieve all three in one setting – *nanofiber atom trap***





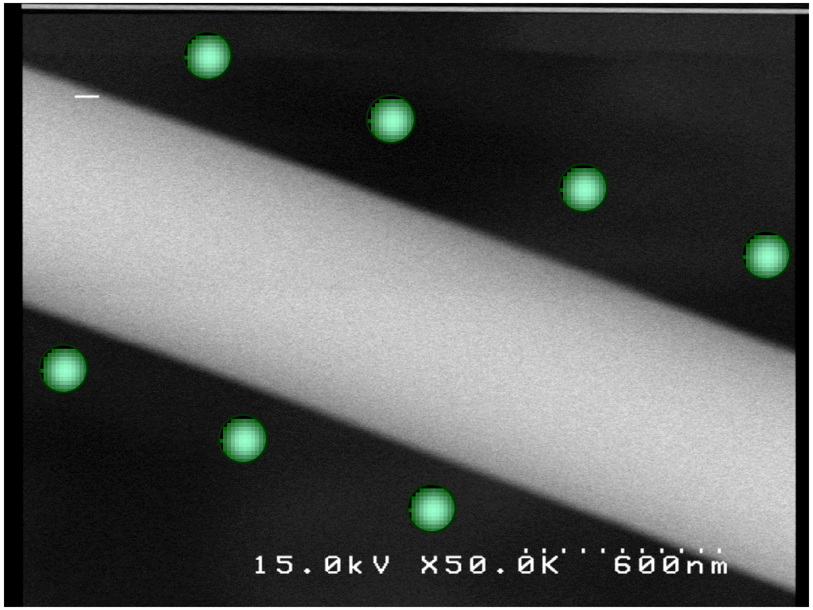


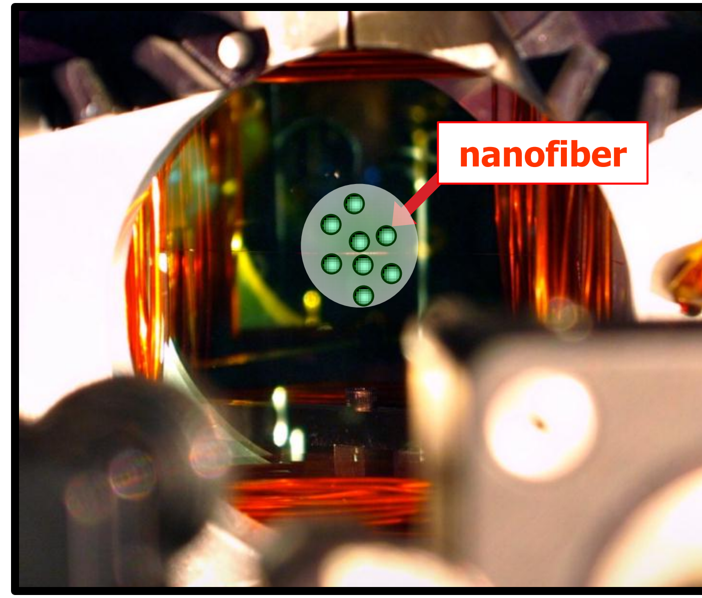


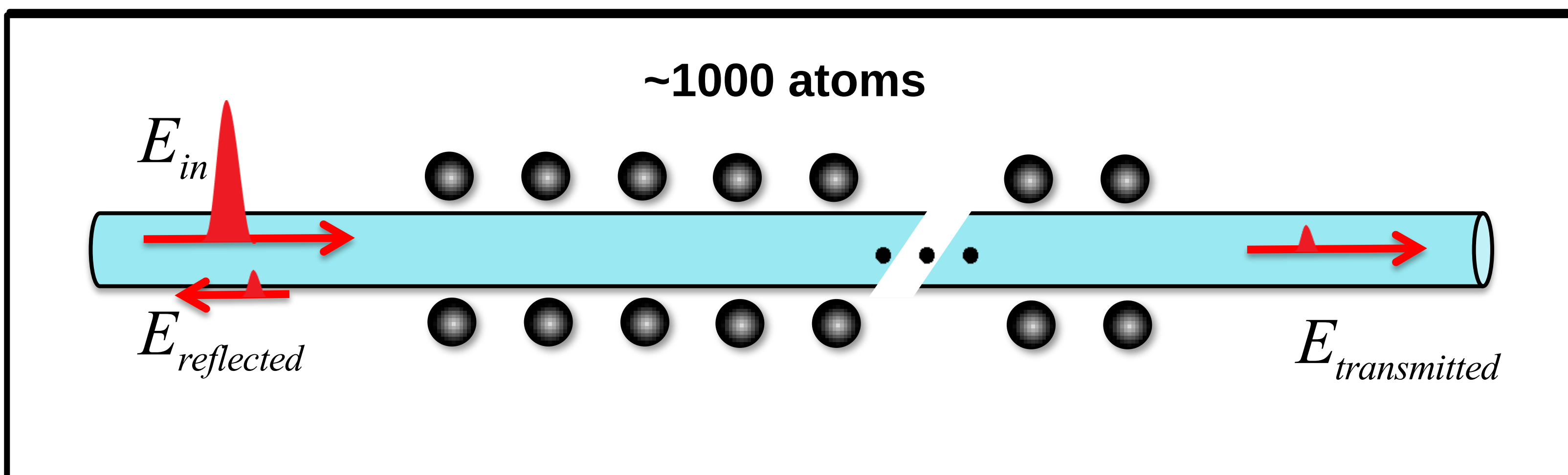
Demonstration of a State-Insensitive Nanofiber Trap

A. Goban *et al.*, Phys. Rev. Lett. **109,** 033603 (2012)

Nano-fiber

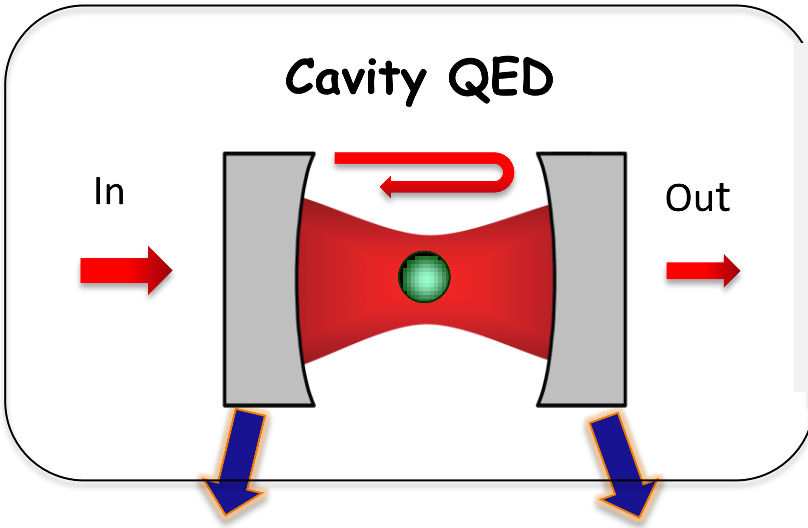






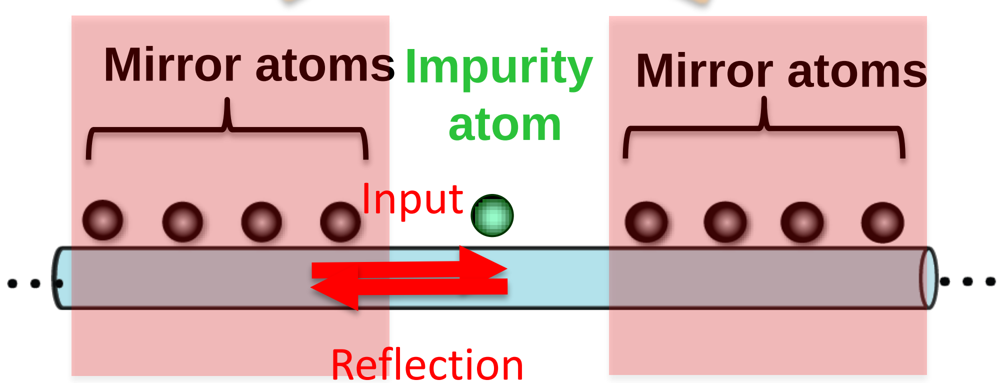
Cavity QED with Atomic Mirrors

D. Chang, L. Jiang, A. Gorshkov & H.J. Kimble, N. J. Phys. **14** 063003 (2012)



Quantum protocols

- -Single photon generation
- -Entanglement distribution
- -Quantum logic
  - - atoms
  - - photons
- - …



Nanofiber issues

- -Two-color traps increase noise sensitivity
- - Ill defined polarizations for trap and probe fields
- - "Noise" from vibrational modes of nanofiber…

Solution →

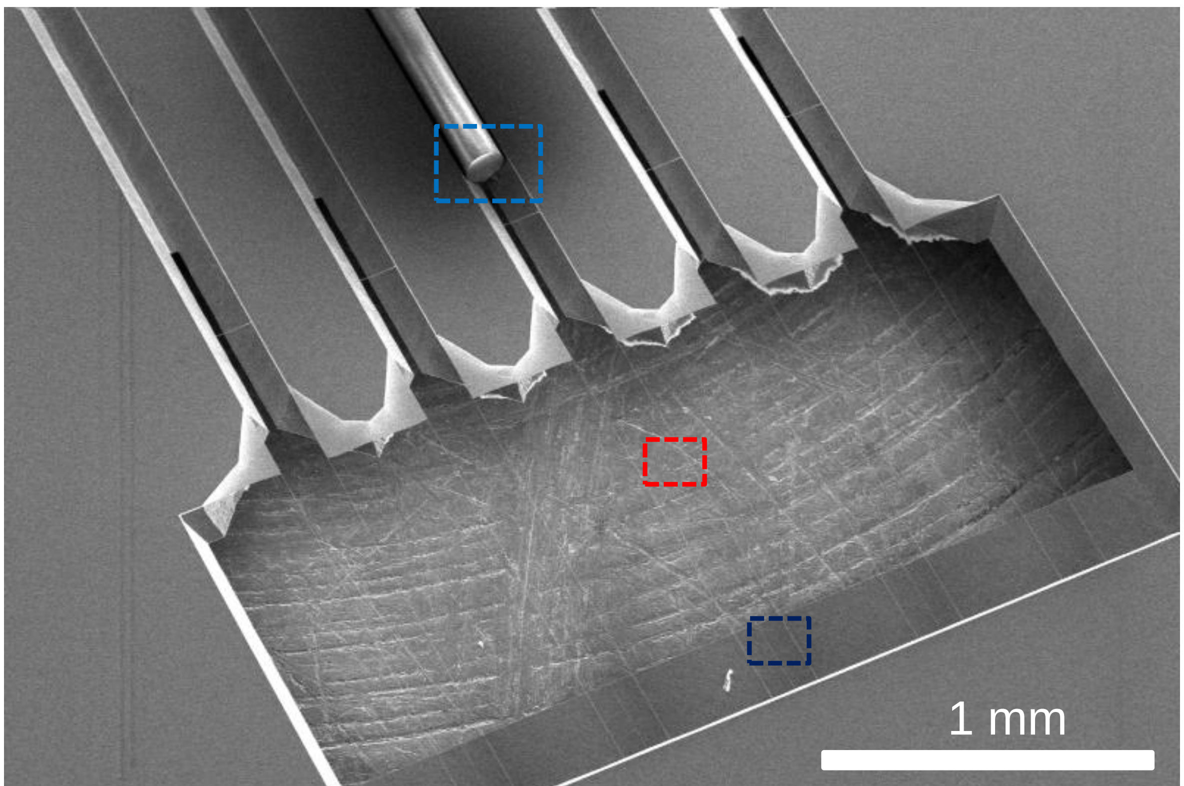
A Surprise!

- Strong coupling regime can be reached with very low cavity finesse $F < 10^3$
- Conventional Fabry-Perot cavity with dielectric mirrors requires finesse $F \approx 10^5$

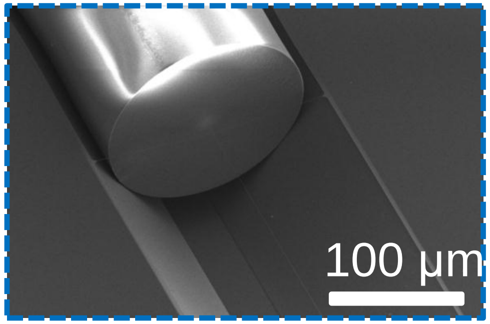
Fiber-coupled chip for atom-light coupling

Oskar Painter, CalTech

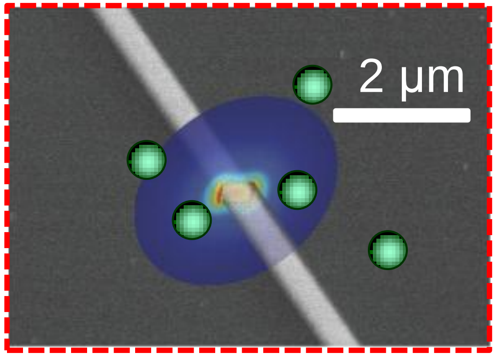
- Clear window for trapping of atomic clouds in Kimble Group MOT
- Arrays of fiber-coupled waveguides (1 shown here) for multiple device testing in a given experiment run



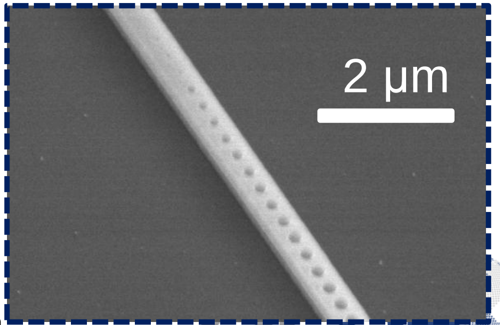
Efficient collection fiber



Evanescent atom-light coupling



Photonic crystal mirrors/cavities



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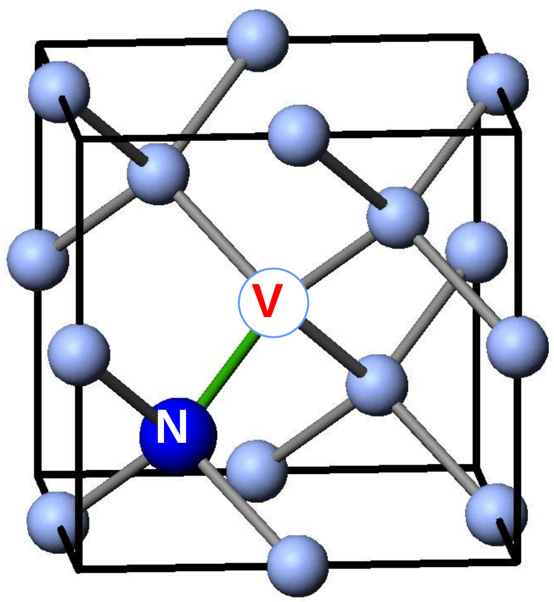
Nitrogen Vacancy Centers in Diamond



NV centers provide

- Room temperature quantum coherence
- Long spin coherence (T_2 ~ 10 ms)
- Optical initialization and readout
- Solid state system
- Reduced nuclear spin environment

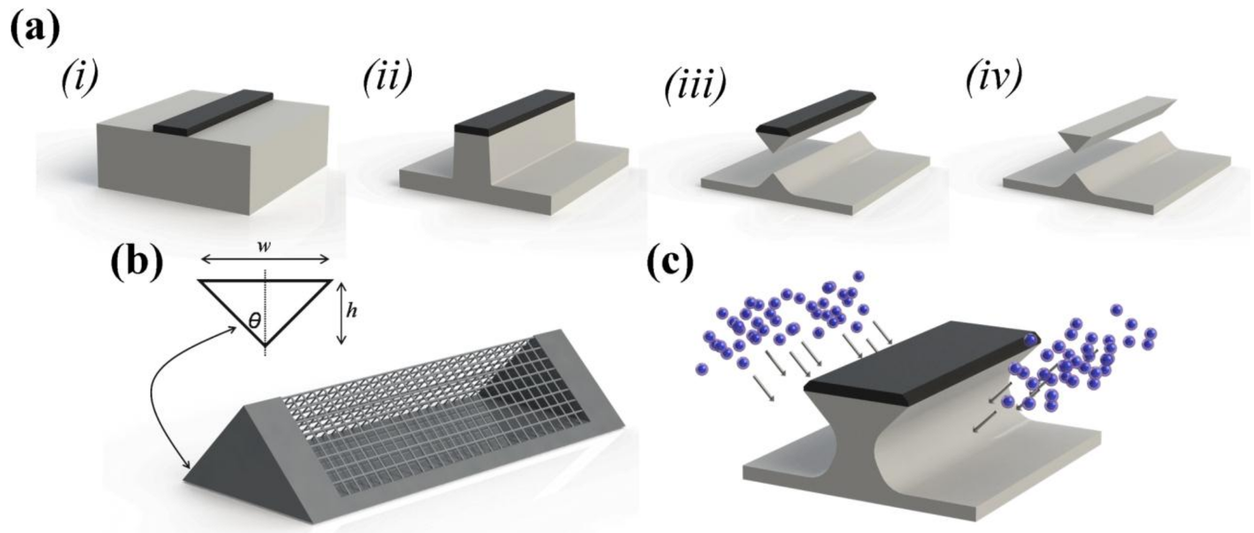
Challenges for quantum information processing:

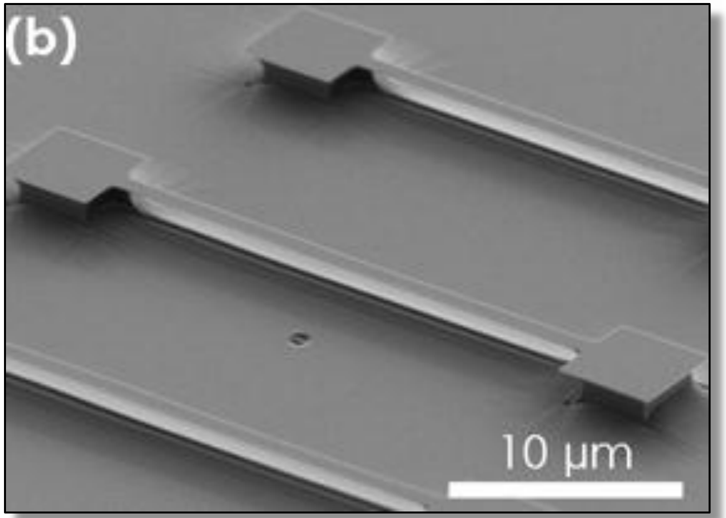
- Creating identical single spins
- Developing scalable quantum memories
- Fabricating hybrid devices

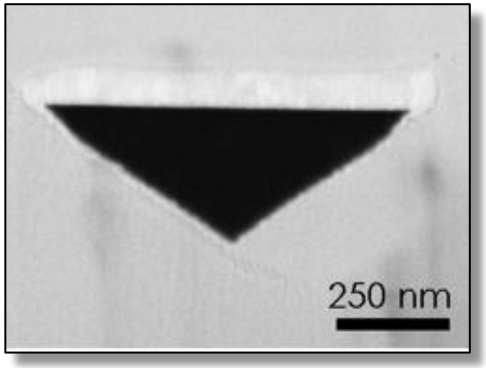
Angle-Etched Nanobeam Cavities

Marko Lončar, Harvard

New approach for fabricating nanostructures from bulk diamond

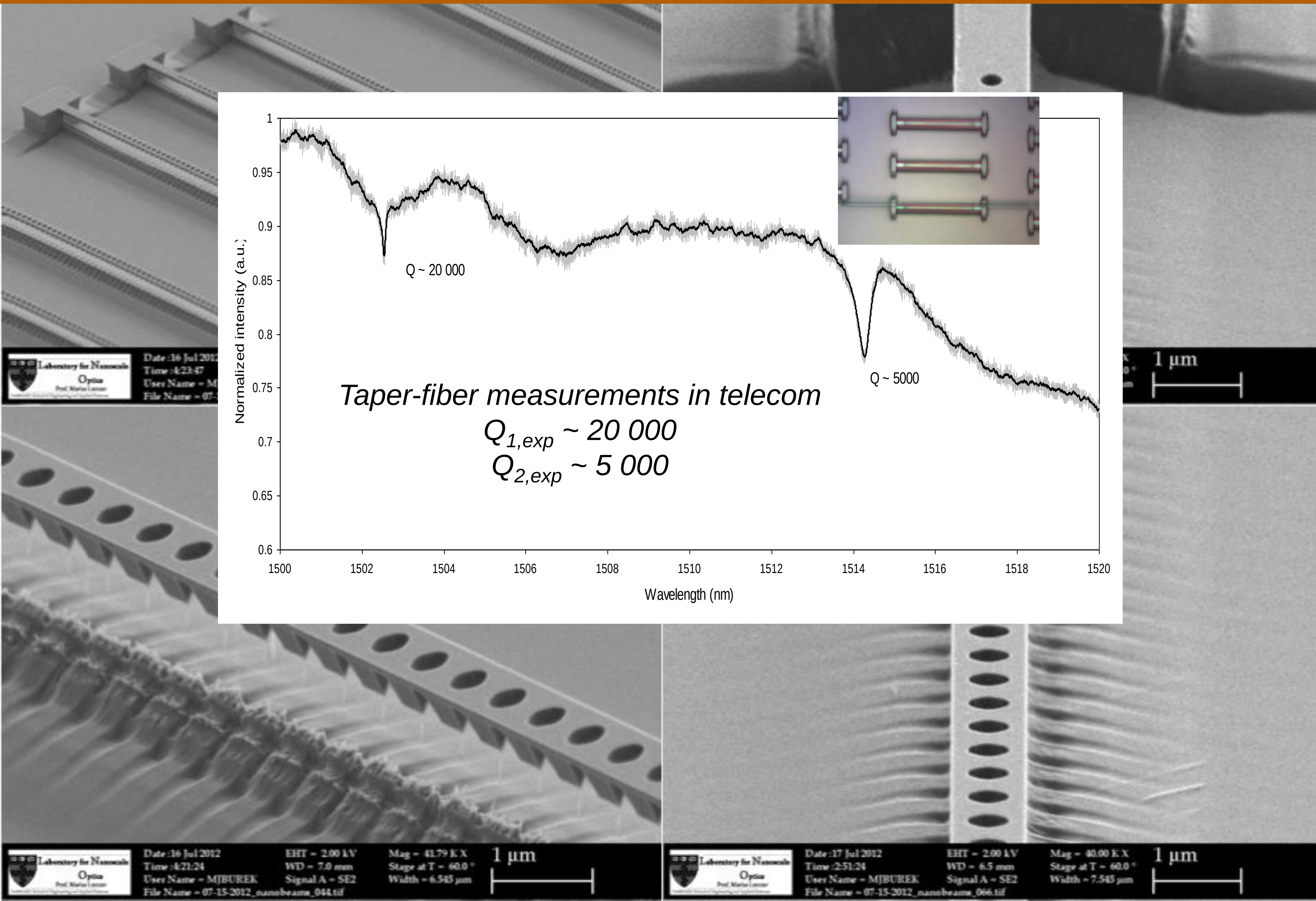




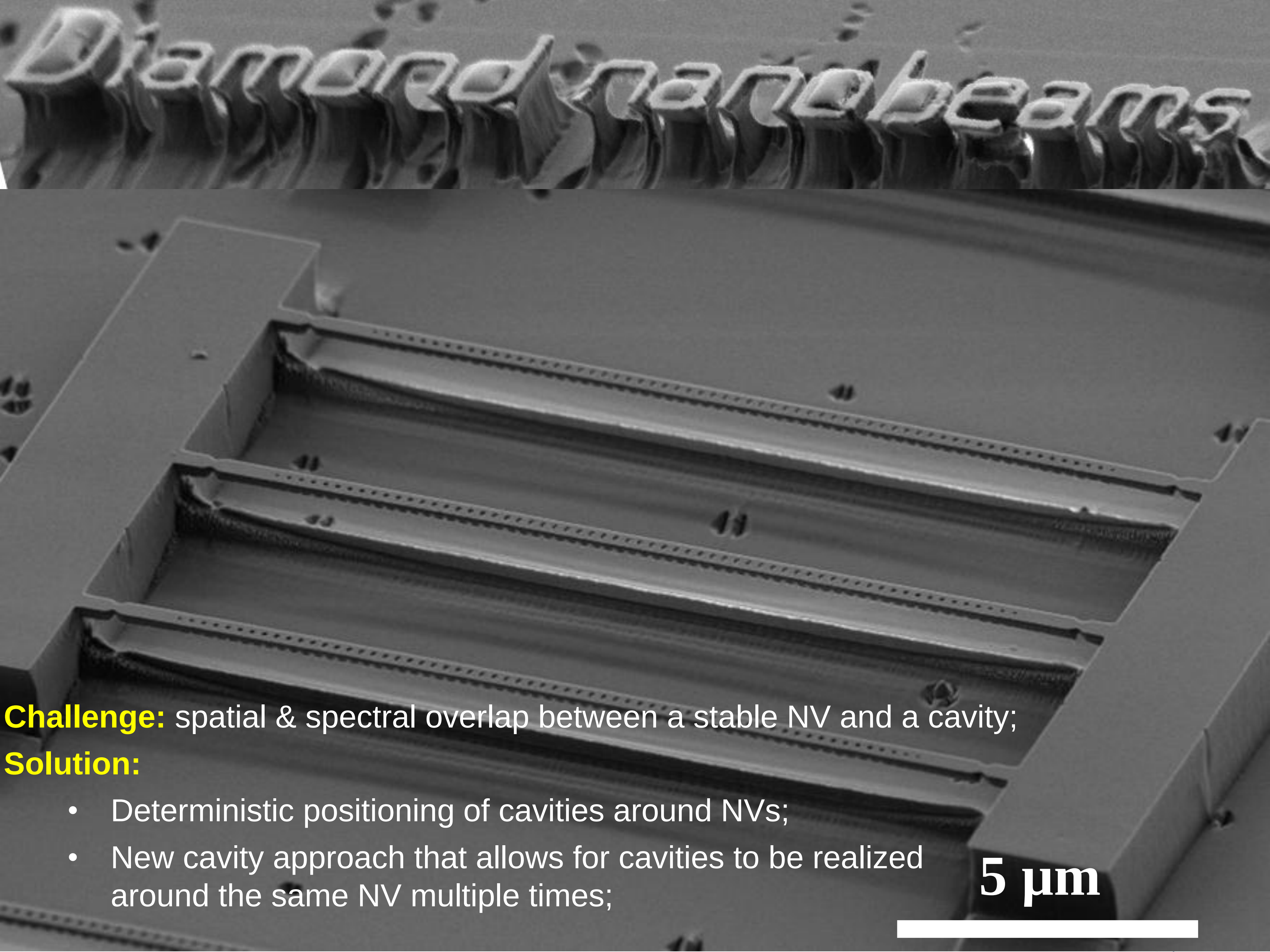


M. J. Burek, N. P. de Leon, et al,
Nano Letters **12**, 6084 (2012)

Angle-Etched Diamond Nanobeam Cavities @ Telecom



Diamond nanobeams



Challenge: spatial & spectral overlap between a stable NV and a cavity;

Solution:

- Deterministic positioning of cavities around NVs;
- New cavity approach that allows for cavities to be realized around the same NV multiple times;

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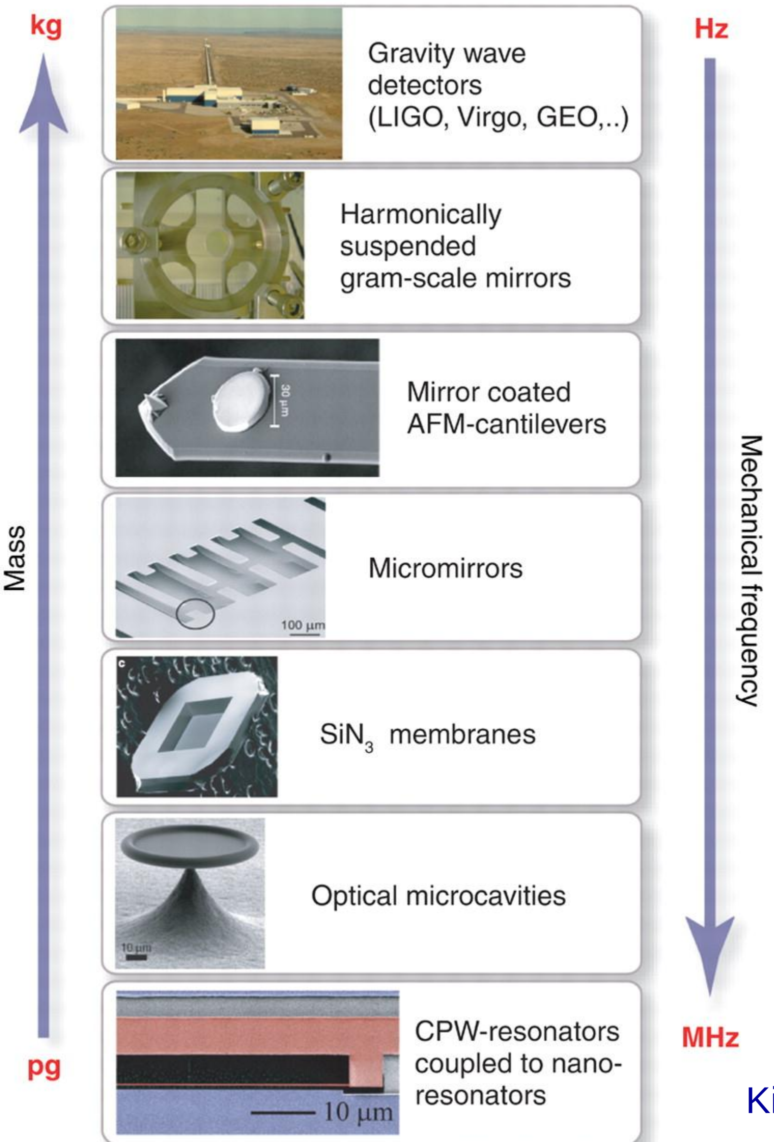
Cavity Optomechanics



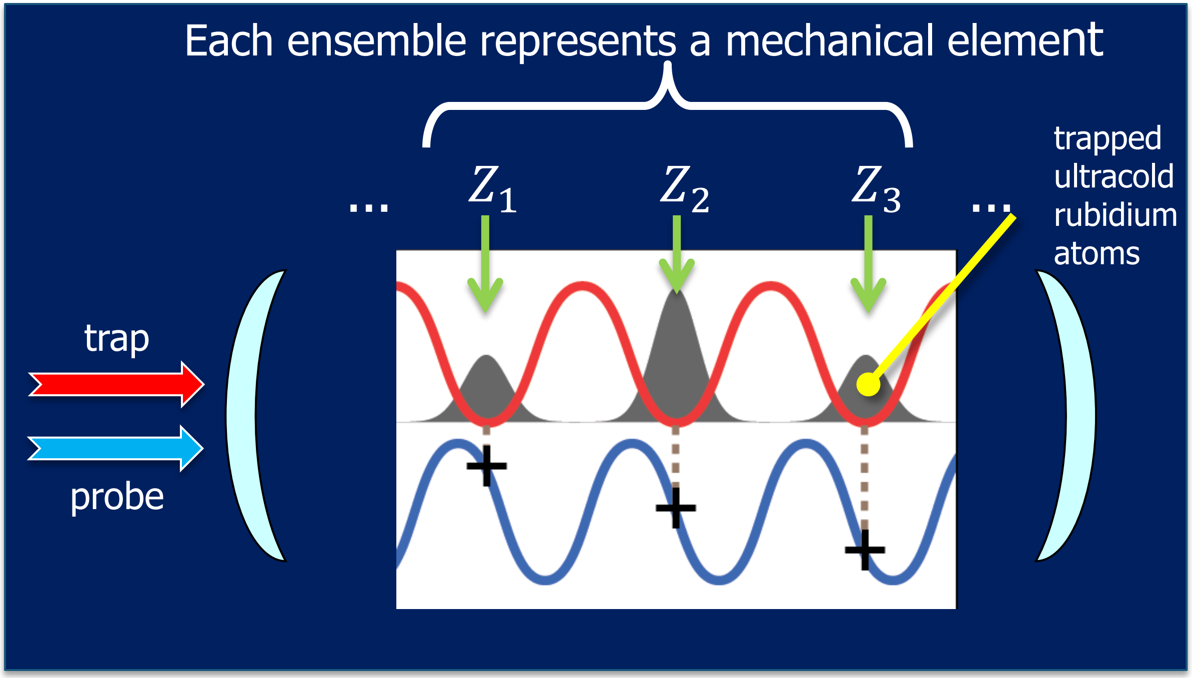
Common goals:

- Dominance of quantum fluctuations over thermal fluctuations
  - cooling mechanical oscillator to ground state
  - reaching quantum limits for sensitivity
- Study and use quantum effects
  - quantifying and evading measurement backaction
  - entanglement of macroscopic object with light
- Route to complex quantum systems
  - Multi-mode systems (optics and mechanics)
  - Optomechanics as link between quantum objects

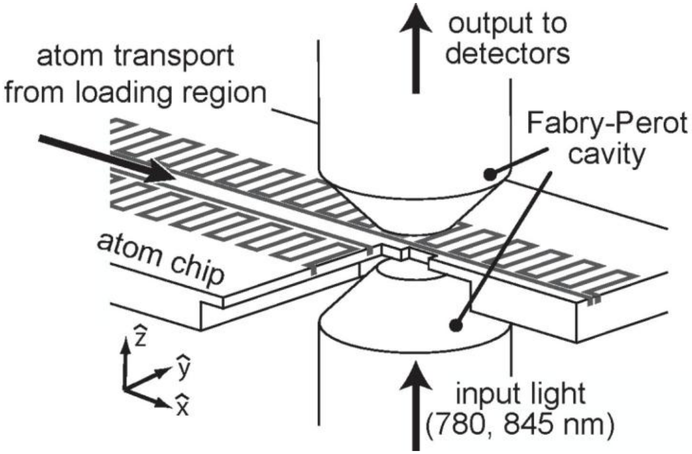
Kippenberg and Vahala, Science **321**, 1172 (2008)

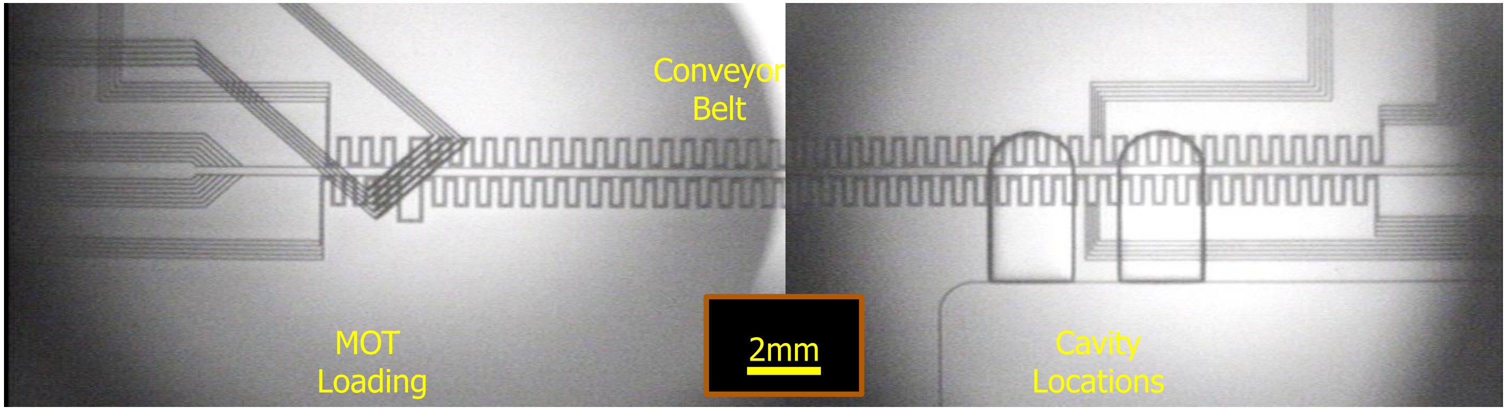
Cavity Optomechanics with Cold Atoms

Dan Stamper-Kurn, UC Berkeley



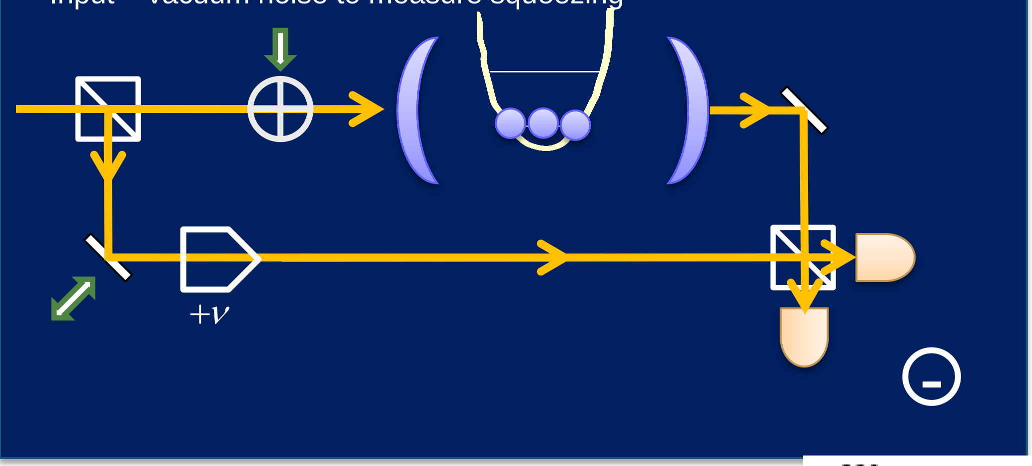
Mechanical oscillator: sheets of atoms





Non-classical light generation

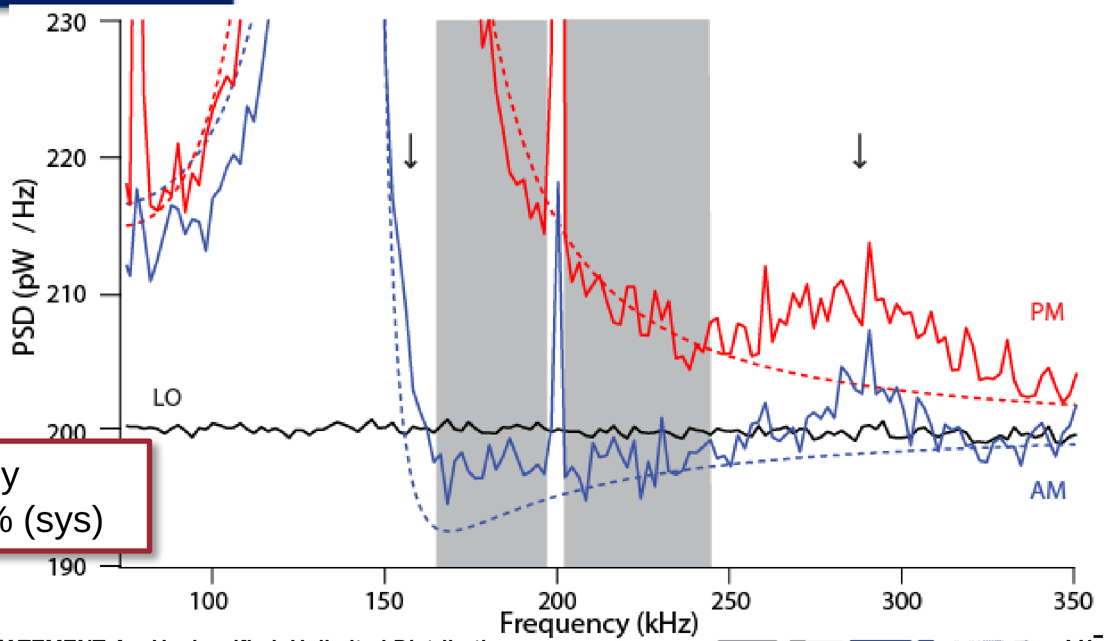
Input = AM tone to measure gain
Input = vacuum noise to measure squeezing



Daniel W.C. Brooks, *et al*, *Nature* 488, 476 (2012)

- Collective atomic motion is driven by quantum fluctuations in radiation pressure
- The back-action of this motion onto the cavity light field produces *ponderomotive squeezing*

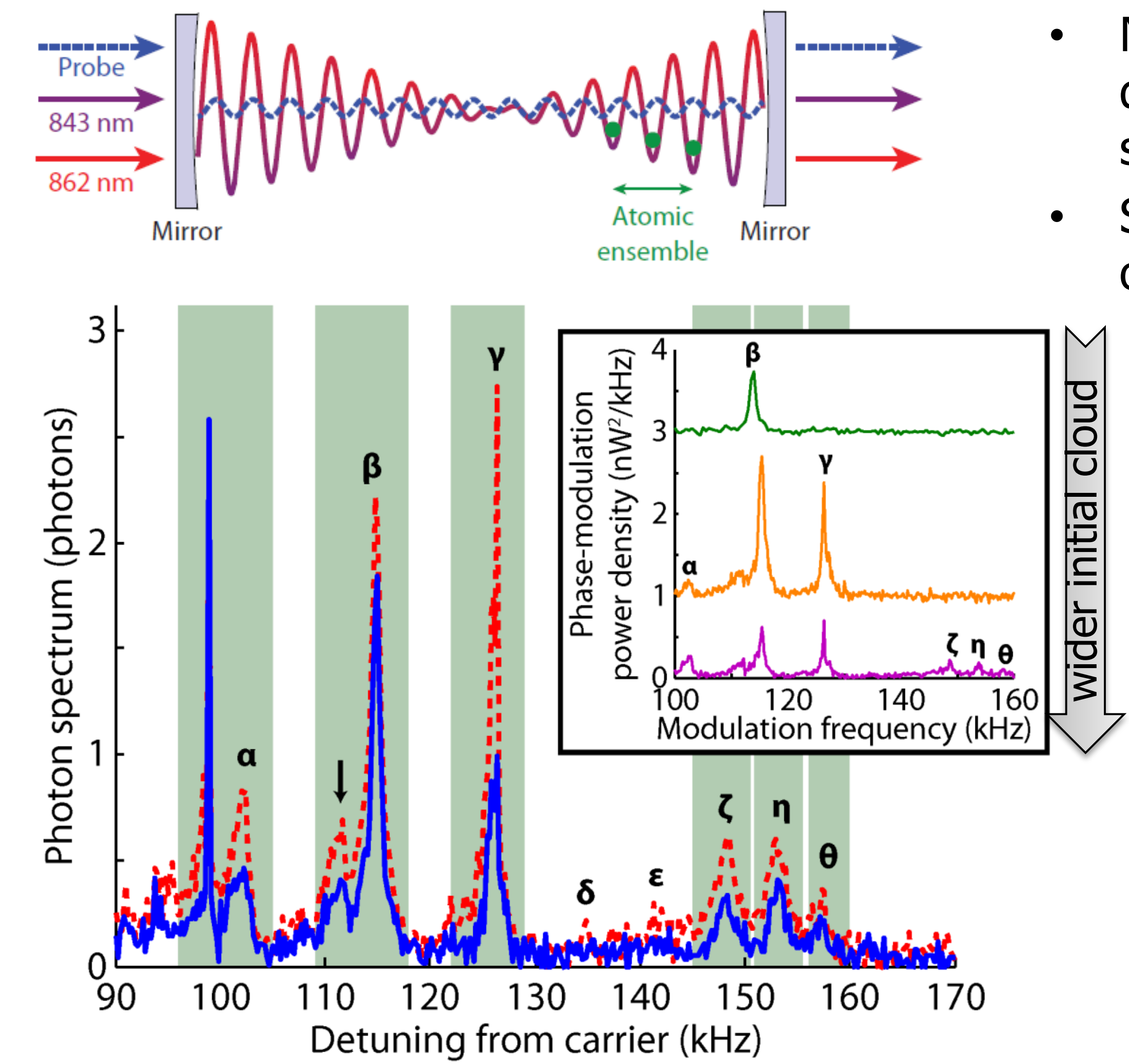
Sub-shot-noise optical squeezing observed



Below shot-noise by
1.4% ±0.1% (stat) ±0.1% (sys)

Next: Cavity optomechanics with a mechanical array

"Optical read-out of the quantum motion of an array of atoms-based mechanical oscillators," arXiv:1210.5218 (2012)



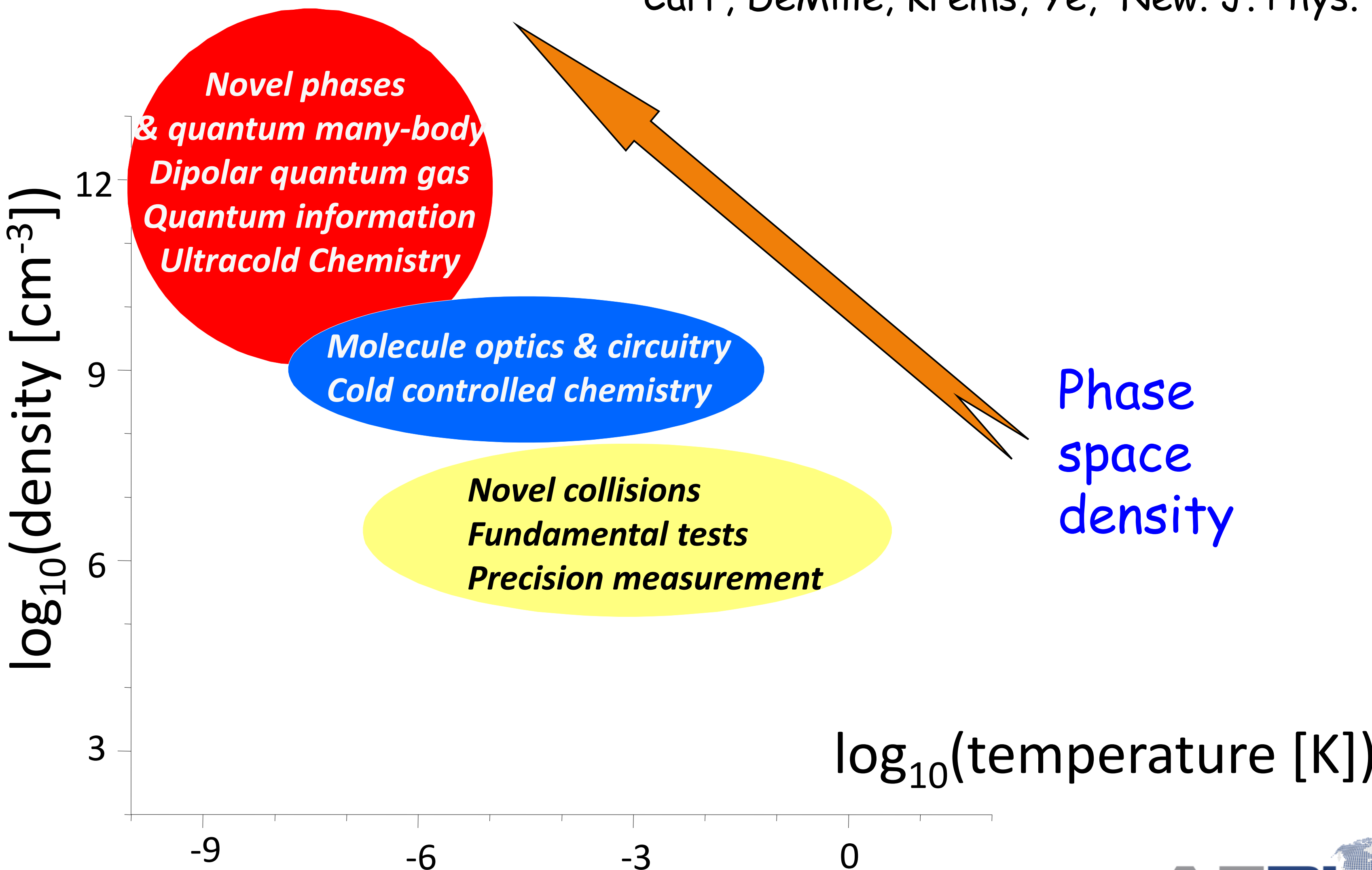
- Nearby lattice sites given different resonances using optical superlattice
- Sideband asymmetry for each oscillator
  - 6 mechanically distinct oscillators demonstrated
  - Motional state of one oscillator can be selectively addressed
  - Nanometer-scale spatial resolution of each mechanical element

Outline

- **Quantum Communication: Quantum Memories and Light-Matter Interfaces (FY11 MURI)**
  - **Strongly Interacting Photons: Vladan Vuletic (MIT)**
    - Cavity-based single-photon transistor where one photon can switch 1000 photons: Wenlan Chen, *et al, preprint*
  - **Atomic Quantum Memories in Nano-Scale Optical Circuits: Jeff Kimble, Oskar Painter (CalTech)**
    - Demonstration of a nanofiber atom trap: A. Goban, *et al, Phys. Rev. Lett*. **109**, 033603 (2012)
    - Cavity QED with atomic mirrors: D. Chang, *et al, N. J. Phys*. **14**, 063003 (2012)
    - Fiber-coupled chip for atom-light coupling: J. D. Cohen, S. M. Meenehan, O. J. Painter (in preparation)
  - **Nitrogen-Vacancy (NV) Centers in Diamond : Marko Lončar, Misha Lukin (Harvard)**
    - Free-standing mechanical and photonic nanostructures in single-crystal diamond: M. J. Burek, *et al, Nano Lett*. **12**, 6084 (2012)
    - PMMA-diamond hybrid cavities, coupling stable NV centers
- **Cavity Optomechanics with cold atoms: Dan Stamper-Kurn (UC Berkeley)**
  - **Squeezed light generation:** Daniel W.C. Brooks, *et al*, *Nature* **488**, 476 (2012)
  - **Quantization of collective atomic motion**: N. Brahms, *et al*, *Phys. Rev. Lett*. **108**, 133601 (2012)
  - **Cavity optomechanics with a mechanical array**: Thierry Botter, *et al*, arXiv:1210.5218 (2012)
- **Ultracold Molecules: Jun Ye, John Bohn (JILA)**
  - **Evaporative Cooling of OH:** Benjamin K. Stuhl, *et al*, *Nature* **492**, 396 (2012)

Science with Ultracold Molecules

Carr, DeMille, Krems, Ye, New. J. Phys. 2009



Evaporative Cooling of OH

Jun Ye, John Bohn, JILA

Benjamin K. Stuhl, *et al*, *Nature* 492, 396 (2012)

Cooling by at least an order of magnitude in temperature and three orders in phase space density!!